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An AUV glider (AUVG), optimized for long range and endurance littoral operations, has been designed, constructed, and operated for an extended period in an adaptive sampling mode as a component of a larger littoral scientific program.

The AUVG, called SLOCUM, is comparatively simple, easy to operate with a small team, and inexpensive to reproduce. The principal operational specifications are:

- Displacement 50 kg
- Range 1800 km
- Endurance 60 days
- Speed, horizontal 0.35 m/s
- Communication: RF LAN and ARGOS
- Navigation reference GPS
- Payload general purpose platform, currently Seabird CTP
- Maximum operating depth 200m
- Batteries - alkaline

Control design approach has been the transfer from the MIT AUV laboratory of both their concept of control architecture, and of the use of the specific software used in the Odyssey AUV with appropriate modification for AUVGs.

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An Autonomous Gliding Vehicle for the Distributed Observation of the Littoral Environment

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An Autonomous Gliding Vehicle for the Distributed Observation of the Littoral Environment

INTRODUCTION: An AUV glider (AUVG), optimized for littoral operations, has been designed, constructed, and operated for an extended period in an adaptive sampling mode as a component of a larger littoral scientific program at LEO-15 (Long-term Ecosystem Observatory Rutgers University).

The AUVG, called SLOCUM, is comparatively simple, easy to operate with a small team, and inexpensive to reproduce. The principle operational specifications are:

- Displacement 50 kg
- Range 1800 km
- Endurance 60 days
- Speed, horizontal 0.35 m/s
- Communication, RF LAN & ARGOS
- Payload, currently SeaBird-CTP, expandable for general purpose
- Operating depth, maximum 200m
- Energy source, alkaline batteries
- Navigation reference, GPS

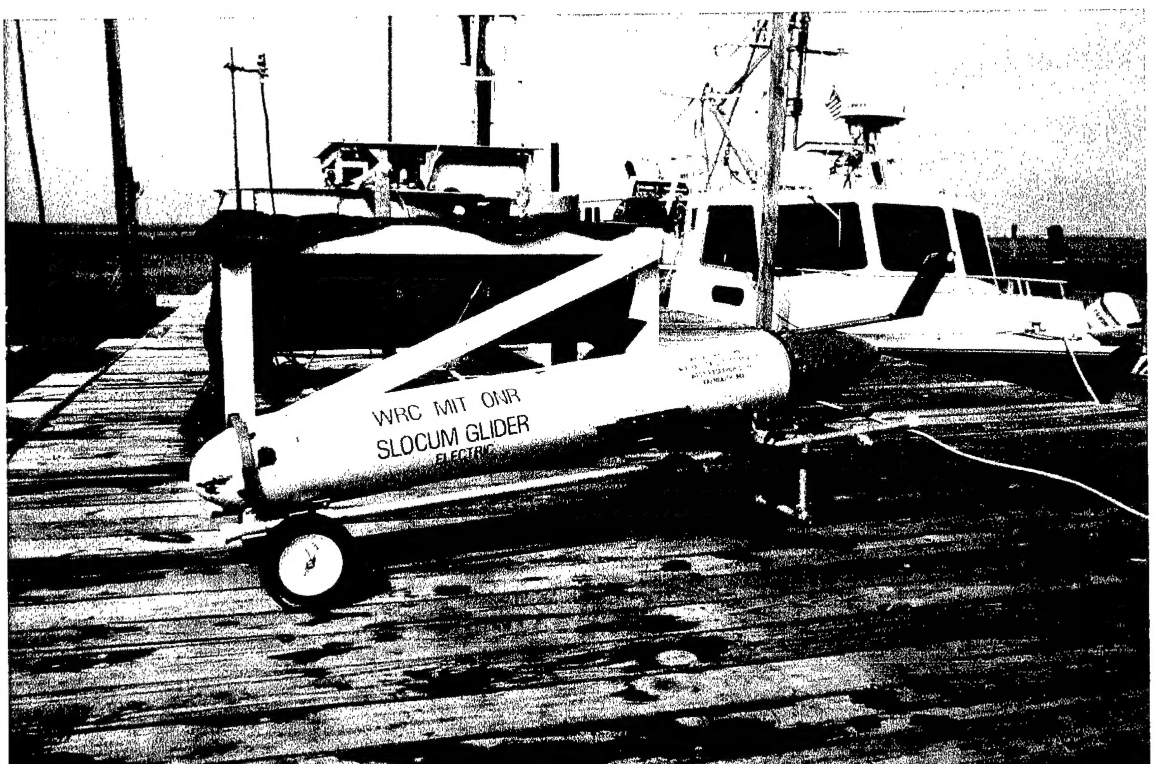

Figure 1 SLOCUM Electric AUVG Post-deployment, LEO-15, NJ

A gliding AUV is propelled by varying the vehicle buoyancy and arranging wings and control surfaces so that it glides downward when denser than water and glides upward when buoyant. It requires no propeller and operates in a vertical

sawtooth trajectory. Propeller and gliding vehicles are complementary and each has important advantages. The principle advantages of AUVGs are:

1) Very suitable for long-range and endurance, if low to moderate speed is acceptable.
2) The sawtooth profile is optional for both vertical and horizontal observations in the water column.
3) Regular surfacing is excellent for capturing GPS and two-way communication, no other navigational aids are required and the system is very portable.

A key design approach has been the transfer from the Massachusetts Institute of Technology Underwater Vehicles Laboratory of both their concept of control architecture, and of the use of the specific software used in the Odyssey AUV with appropriate modification for AUVGs.

DESIGN: At the beginning of the STTR program WRC (Webb Research Corporation), had already carried out and documented (Ref. 1) tests of a thermally powered glider under an ONT WHOI contract (Ref. 2) and had been engaged in the preliminary design of a deep ocean battery powered glider through MURI-WHOI (Ref. 3, 4). We were confident that a glider for littoral operations was practical and could estimate the operations envelope.

The principal tasks were:

1) Replace the simple controller flight recorder first used in the 1991 trials with a controller with substantial development potential. Adapt the control concepts and architecture developed at the MIT laboratory, and use or modify the 7th generation Odyssey AUV software in enhanced microcontroller hardware constructed at WRC and debug and demonstrate the resulting performance.

   - The controller is a Persistor CF1, based on a Motorola 68338 processor. This board has low current consumption capability and supports the use of CompactFlash cards and miniature hard drives enabling very large amounts of data to be stored. The Persistor is mated to a specifically designed hardware interface board, which supports actuators, communications, sensors, etc.
   - Controller code is written in C and architecturally is based on the Odyssey AUV layered single thread approach where each task is coded into a behavior and behaviors can be combined in almost any order to achieve flexible and unique missions. These behaviors can also be constructed to deal with more complex issues such as dead-reckoning navigation, current correction, and adaptive sampling.
   - Each device is labeled as a sensor and is logged every time that the value changes during a mission. This data is retrieved as a binary file and is post-parsed into a matrix which allows one to re-play flight dynamics or to

easily construct graphical views of vehicle performance or scientific data. A subset of the sensors can be chosen as a science data package so as to reduce surface radio transmission time allowing near real time data collection.

- The AUVG can have in memory any number of pre-written missions that can be called or a new mission can be created, downloaded to the Glider via the RF LAN and run. Mission changes might include different inflect depths, new GPS waypoints, or turning a behavior on or off such as current correction. Mission files are small text files and it is certainly feasible to have these automatically written, downloaded and run based on an external event to permit adaptive networking of vehicles, see "future developments" below.

2) Optimize the performance of the prototype glider used in the 1991 field trials.

- As discussed above, the advance in micro-controller and better capability to view the vehicle data has aided enormously in quickly building our knowledge base of vehicle performance and allowed fine-tuning of vehicle dynamics.
- One of the limitations of the prototype glider was in communications. It became apparent that the umbilical cord approach where one would have to collect the vehicle and plug into it to collect the data set was not going to be useful with an AUVG. This led to the integration of a line-of-sight RF-LAN system made by Freewave Modem as the main communication link to the gliders. This has proven to be very successful and is now used by many other AUV groups and even as a method of shore to ship networking on the web to allow for real-time adaptive sampling. We have shown this to work from a repeater at 200 feet high to the glider in a 1' sea state to a distance of 21 nm. With a 4 - 6' sea state the operations drop to approximately 10 nm due to wave shadowing of the signal. A direct link is rated at 115 Kbaud, a link through a repeater modem approximately halves the data rate, and of course rough sea conditions reduce the effective baud rate even further. The next stage is to integrate a satellite communications system, see "future developments" below, while retaining the RF modem system for high speed local communications.
- Other advances were to enhance the robustness and hands-free operation of the AUVG's. This is covered in detail below with the redesign for littoral operation. During a July 2000 field trial at the Rutgers LEO-15 research site in Tuckerton, NJ, a Slocum electric-powered glider ran for planned deployment of 10 continuous days without having to be brought ashore. Diving to an average of 15 m every 2.5 minutes, triggered on depth and altitude, the glider collected over 5000 cycles or profiles worth of ctd data. Surfacing every 45 minutes to obtain a GPS fix, this data was collected in near-real time via the RF-LAN and assimilated into the Rutgers prediction model. The vehicle was sent on varied missions

covering specific areas to capture an upwelling event and including one 20 km transect run which at its end was 20 nm off-shore, Figure 2. During this trial period, direct control of the glider was transferred several times from Tuckerton, NJ to WRC in Falmouth, MA – using an internet to RF-LAN connection. Typical runs would include on board current correction, Figure 3. An example of data sets can be seen in Figures 4 thru 7 based on a transect shown in Figure 8.

3) Create a design for littoral operation. At the project beginning, it was clear that a design for littoral use would be different than designs for deep ocean use and experience has enforced this judgement. Described below are the subsystems as developed for coastal use.

- In shallow water, dives will be short in time and space, with inflection close to the bottom. We can operate in very shallow water, approximately 3m, with full performance in depths of 8 m. First the bottom must be detected and the altitude measured. This is done with a Benthos/Datasonics model PSA-916, 0-100 m range with the transducer mounted in the flooded tail cone at an angle such that it points vertically when the glider is operating at a typical downward glide angle. The deep inflection can be programmed for fixed depth, fixed altitude, or the first to occur. The performance of the altimeter is adequate and can probably be improved. A review of alternative altimeters will be undertaken.
- A second component of shallow water inflection is inflection speed, both change of buoyancy and rate-of-change of pitch. The usual approach to buoyancy change is to pump or vent hydraulic oil between an internal reservoir and an external bladder located in the flooded tail section. We departed from this approach and used a sea water pump which moves sea water directly into and out of the nose of the vehicle through a port on the nose centerline (the stagnative point). It is desirable to inflect quickly in shallow water, typically in approximately 15 seconds. This would require substantial tubing diameter if the fluid is moved any distance, however we move the water through a short 12 mm diameter port in the nose. The fluid movement also provides the moment for changing pitch (water moves into the nose making the vehicle nose heavy when diving, similarly making the nose buoyant when rising). Reliable inflection within 1 m of the bottom is possible and there is little loss of vehicle kinetic energy through the inflection.

PUMP: The pump is a single-stroke design using a 90 watt Maxim gear motor, a 5/8 in. lead screw and ball nut, a rolling diaphragm seal and potentiometer feedback for volumetric control. At full stroke the displacement change is +/- 225 ml.

An air pump is incorporated to provide additional buoyancy once the glider has reached the surface. A flexible urethane bladder is located in the

flooded tail cone, and approximately 1400 ml of air can be pumped from the interior of the hull providing very useful reserve buoyancy elevating the antennas in the tail fin and enhancing vehicle visibility for recovery. This air is vented inward via a latching valve for descent.

BATTERY: The battery consists of 100 Alkaline D cells, 10 in series x 10 parallel strings. The complete battery pack can controllably rotate and translate to give the required roll for steering and provide a small pitch moment to trim the pitch provided by the seawater pump. Generally this trim is not used for regular operations, however it is very useful for exploring the performance envelope of the vehicle. Alkaline cells were chosen for economy and safety. The replacement of the battery pack is approximately $300, however they can be replaced with lithium cells for substantially improved performance, or lithium ion rechargeable cells (as in the REMUS AUV) can be used and would provide multiple cycles of recharge which could be very effective in some applications.

HULL AND HYRODAULIC DESIGN: The cylindrical main hull of 21 cm OD aluminum alloy was chosen for its simplicity, economy, and expandability, that is the length can be changed to accommodate alternative payloads. The nose cap is a machined pressure resistant elliptical shape, and the tail cap a truncated cone plus a free flooded volume enclosed by a composite fairing.

The tail wet volume encloses a 10 KHz pinger used for telemetry and emergency relocation, a spring-loaded emergency jettison weight, the air bladder, the controller umbilical power switch, and the sensor payload.

Composite wings are swept at 45 degrees. In all operations, particularly coastal work, there is a risk of entraining weed or debris on the wings or tail causing major degradation in gliding performance and for littoral gliders a sweep angle of 45 degrees or more is recommended.

In the low Reynolds number regime in which the glider operates, approximately 30,000, their un-cambered ("razor blade") wings are very suitable; these are tapered in thickness over the span, and made of a carbon-epoxy composite.

TAIL: The tail fin mounted on a short longitudinal boom, Figure 1, serves two purposes. It is required to provide yaw stability and the short boom increases its stabilizing moment. Horizontal tail planes are not required, pitch stability is provided by the wings which are mounted aft of the center of buoyancy.

By necessity of providing a low drag communication path suitable for high pressure ratings, the tail fin also contains three antennas: GPS, RF-LAN,

and ARGOS. The dimensions are 3.75" wide by 7" tall by 0.125" thick. This WRC design has proven to be popular and is now in use with other AUV developers around the world.

When stationary at the surface an air bladder in the flooded tail cone is inflated, using air from the hull interior. This provides 1400 ml of reserve buoyancy and the glider equilibrates with the tail elevated, and the boom holds the antenna clear of the water. Even with the air bladder, the buoyancy is modest, approximately 3% of displacement, however visual observation shows that the antenna remains clear of the water in moderate sea states (Figure 11) and line-of-sight communications have been demonstrated to a maximum of 20 n miles via a 200' repeater tower on shore.

STEERING: The steering is accomplished by rolling the vehicle, so that a component of the wing lift provides a yaw moment. This steering by gravity shift is similar to steering a hang glider. This approach to steering was used in the 1991 prototype glider and has since been used in numerous designs, however in the littoral environment rolling to large angles interferes with altimeter operation, and the roll is restricted to approximately +/- 15 degrees. Overall the steering can benefit from improvement as discussed under "future developments" below.

Optimum gliding performance is defined as minimum joules per meter traversed horizontally at a given horizontal speed. With the current design, the optimum performance is achieved with a glide angle of approximately 25 degrees ref. horizontal. The analytical approach to optimizing performance is described in Ref. 4.

SENSORS: The complete system, both hardware and software, is designed as a vehicle able to support a family of sensors. At the end of Phase II it carries a CTD system developed in cooperation with Seabird Electronics. The physical configuration is shown in Figure 9. The design is a balance of insuring free flow of undisturbed water, low drag, mechanical ruggedness to withstand abuse during deployment and recovery, and minimum vulnerability to weed pick up.

An example of observations is shown in Figures 4 thru 7, and a comparison between the glider in normal operation and three nearby conventional cast is shown in Figure 10.

Space for additional sensors is available in the flooded tail cone, and the main glider hull can be lengthened readily to provide volume and buoyancy for additional sensors.

PARALLEL RESEARCH: Under ONR MURI contract (Ref 3) WRC is creating a similar glider which harvests propulsion energy from the ocean thermocline. This vehicle design is intended for very extended operation in the deep temperate and tropical ocean, goals are 40,000 km range, five year endurance. We feel very fortunate to be working on these two programs in parallel, for the agile littoral glider serves as an admirable test bed. It can be prepared for and execute numerous tests within a few hours in a nearby lake. One or two people are adequate for a lake trial. The programming and control of all operations and the data readout are centered in a small truck, using the RF-LAN communication.

The control and data algorithms are shared by the two AUVGs with minor differences associated with the two types of buoyancy engines. Both vehicles share many component sensors, and test procedures. The thermal SLOCUM, however has a stronger hull suitable for deeper diving to 1400m.

The thermal SLOCUM is more complex and slightly less mature than the littoral or battery powered SLOCUM. It is our plan at WRC to offer both for sale in the ocean research community and continue aggressive development of these vehicles.

FUTURE DEVELOPMENTS: The long-term goal is an active Phase III, that is the sale of gliders, both littoral and thermal, for application in appropriate ocean and lake research programs. Several investigators, especially David Fratantoni, Woods Hole Oceanographic Institution (WHOI), and Scott Glenn, Rutgers University already have plans for specific scientific application, shown on the attached commercialization report, especially following the ten day operation at LEO-15. There is a challenge on a successful Phase III. Users expect to purchase SLOCUM for approximately the cost of construction and the continuing development and improvement can only be partially funded out of sales income. Continuing modest support for development from ONR is needed.

In the short term we request that the SBIR Phase II option be authorized and we propose the following option program to expand the AUVG capability.

1) Bring to life software to manipulate and distribute the glider data to the web, and permit control of multiple vehicles from remote sites. A WHOI volunteer (Katarzyna Niewiadomska) has done about 70% of this job, we would complete it (test, demonstrate and use). Automation is one of the fundamental goals of the AUVGs. The system has been architected to allow a shore-based computer to receive inputs from a number of AUVGs and other sensor types in the field and to then direct a fleet of AUVGs in an adaptive array. The automation also includes collecting science data files at each GPS surfacing, and sending the vehicle off with the appropriate mission.

2) Improve the steering: Our present steering design – roll to allow a

component of wing lift to create a yaw moment – is likely satisfactory in deep operation, however in the very energetic littoral environment with frequent inflections near the active surface and considerable internal shear it would be very beneficial to have more aggressive steering. We think the glider can be nimble enough to make its way to the beach, to turn in three times its length.

3) Improve communications: We are presently using line-of-sight RF-LAN with ARGOS backup. Communications should incorporate and demonstrate a global satellite system, ORBCOMM, GlobalStar, TMI, Vistar or equivalent. This also includes streamlining and optimizing the data files, reworking the antenna and tail fin.

4) Refine the drawings and software to incorporate numerous incremental changes and improvements discovered during construction and field operations.

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1.) Paul J. Somonetti, "SLOCUM GLIDER, Design and 1991 Field Trials", Webb Research Corporation Internal Report, September 1992.

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3.) Woods Holes Oceanographic Institution, Purchase Order Number M100151.

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5.) Henry Stommel, (April 1989), The SLOCUM Mission, Oceanography, pp 22-25.

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7.) Anna M. Galea, (1999). Various Methods for Obtaining the Optimal Path for the Glider Vehicle in Shallow Water and High Currents. *Proceedings of the 11th International Symposium on Unmanned Untethered Submersible Technology,* August 23-25, 1999. Published by the Autonomous Undersea Systems Institute, pp 150-161.

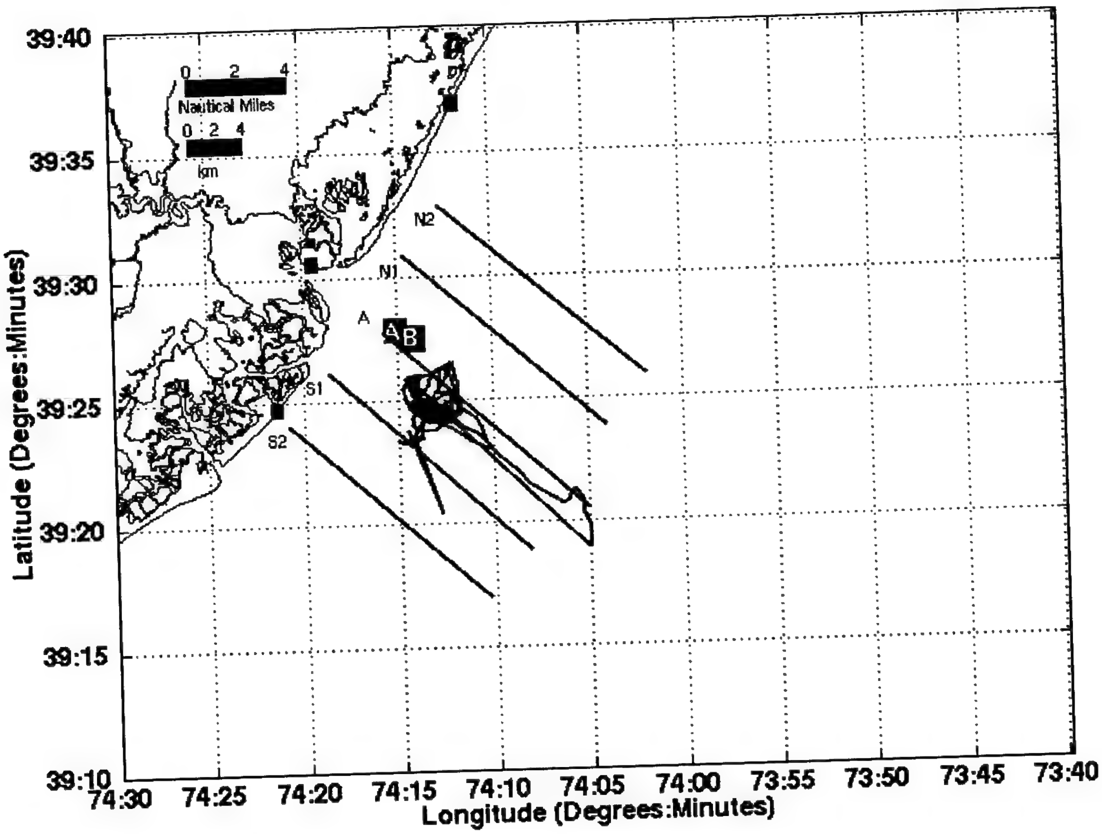

Figure 2 Slocum Electric Trajectories 10 days operation

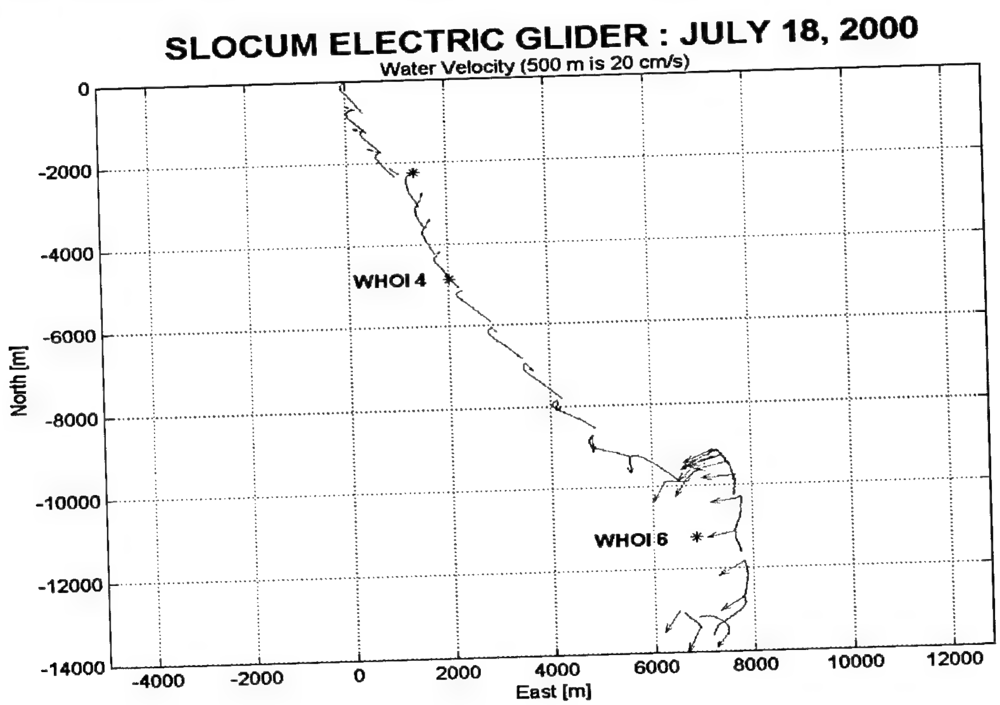

Figure 3 Transect with current correction

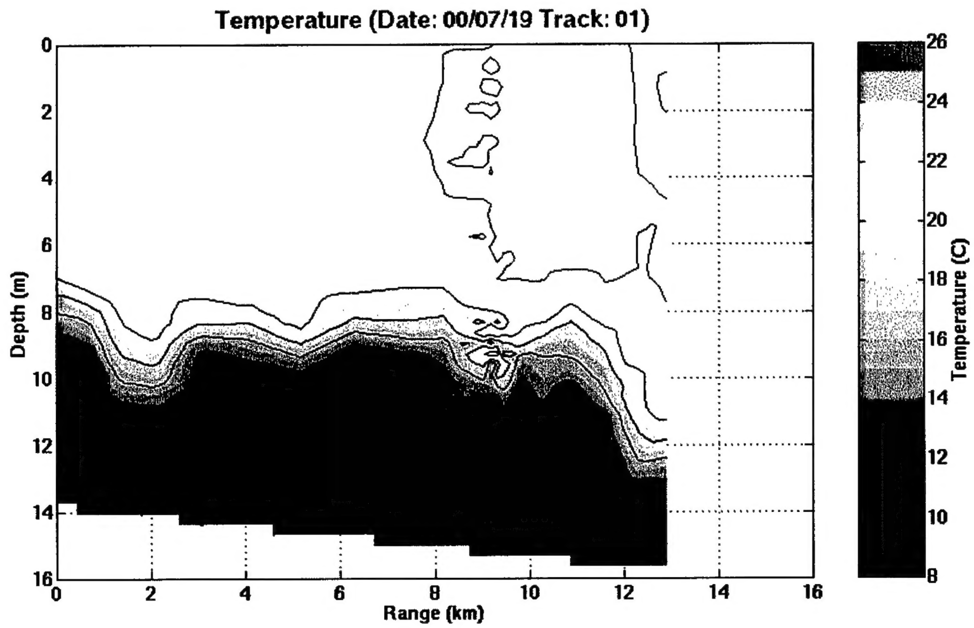

Figure 4 Downcasts at GPS fixes

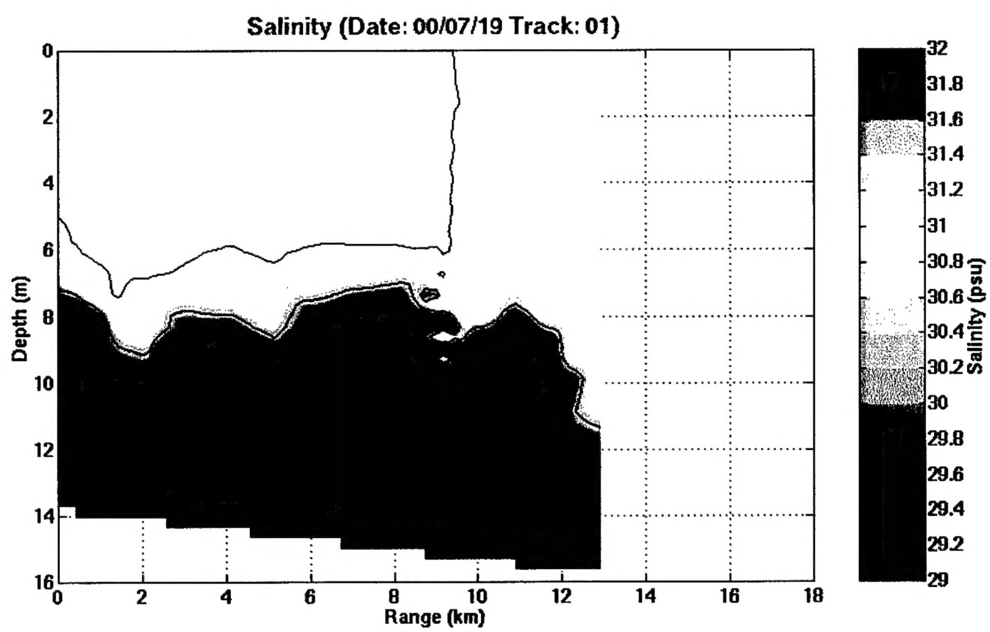

Figure 5 Downcasts at GPS fixes

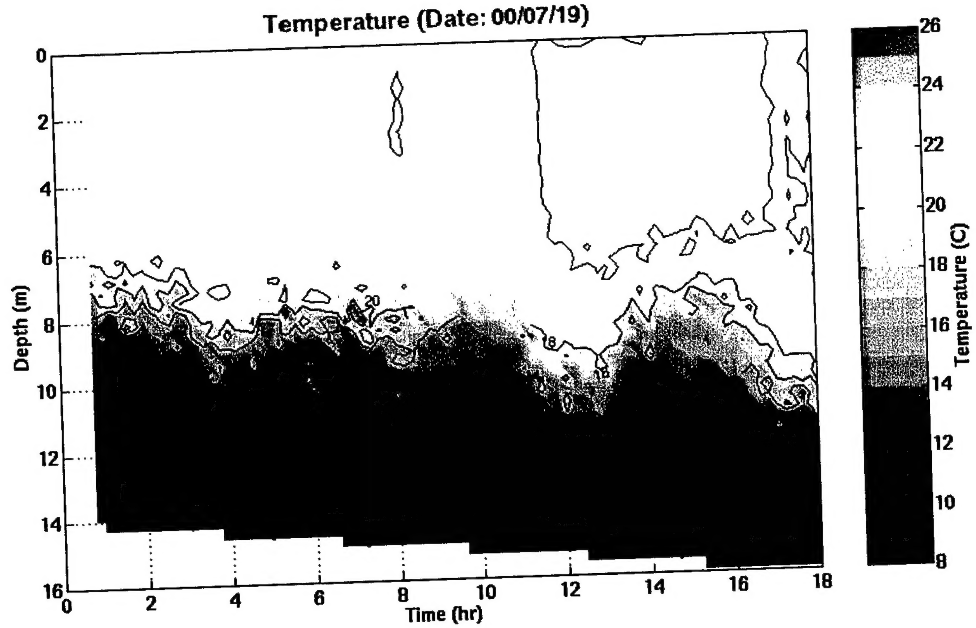

Figure 6 Casts by time

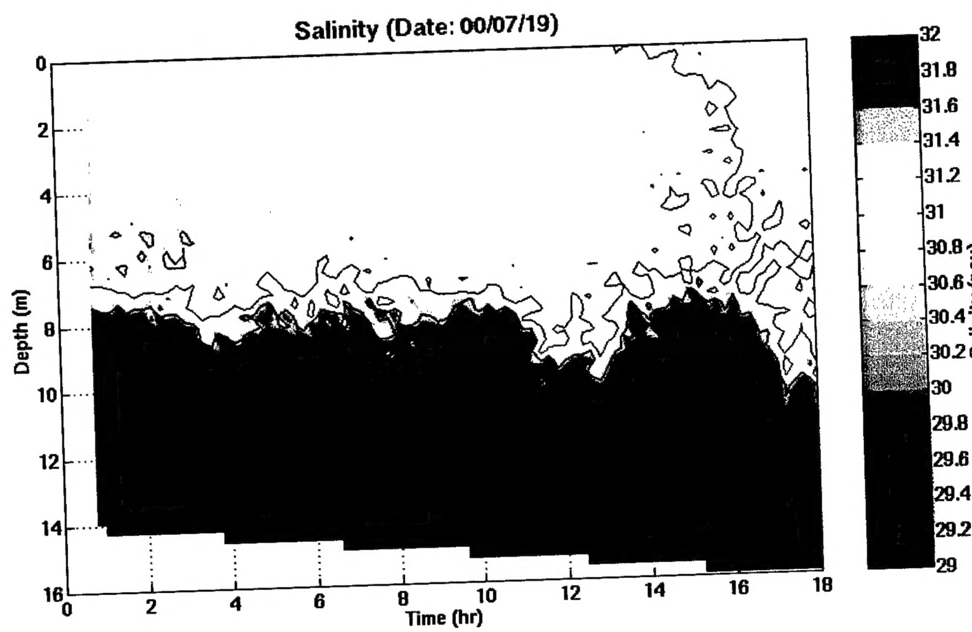

Figure 7 Casts by time

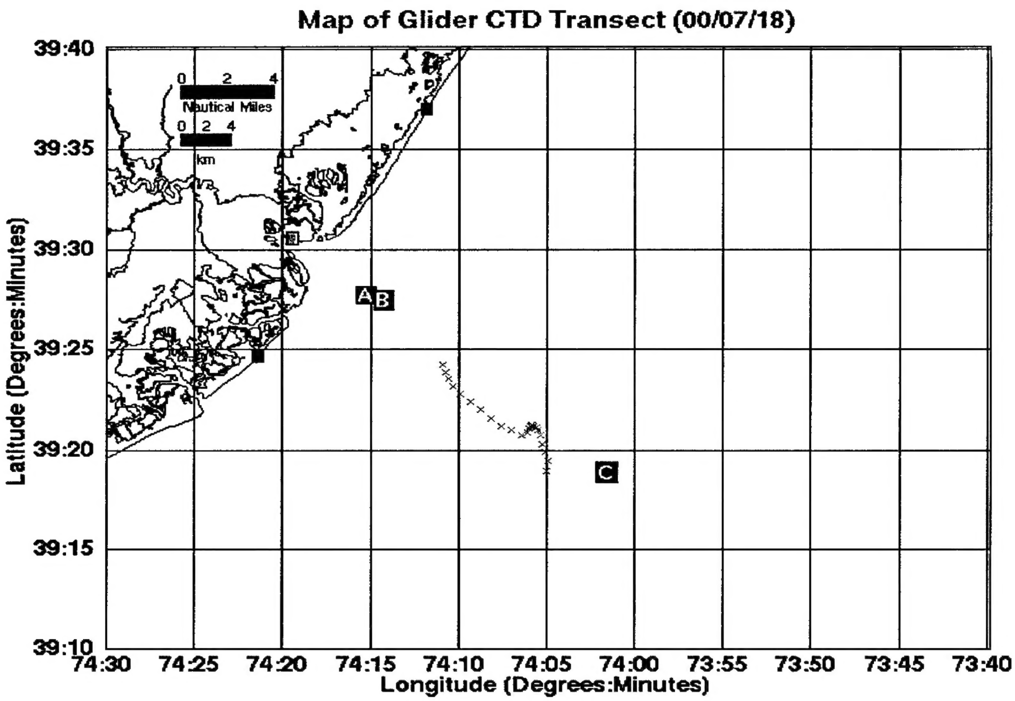

Figure 8 Transect Map

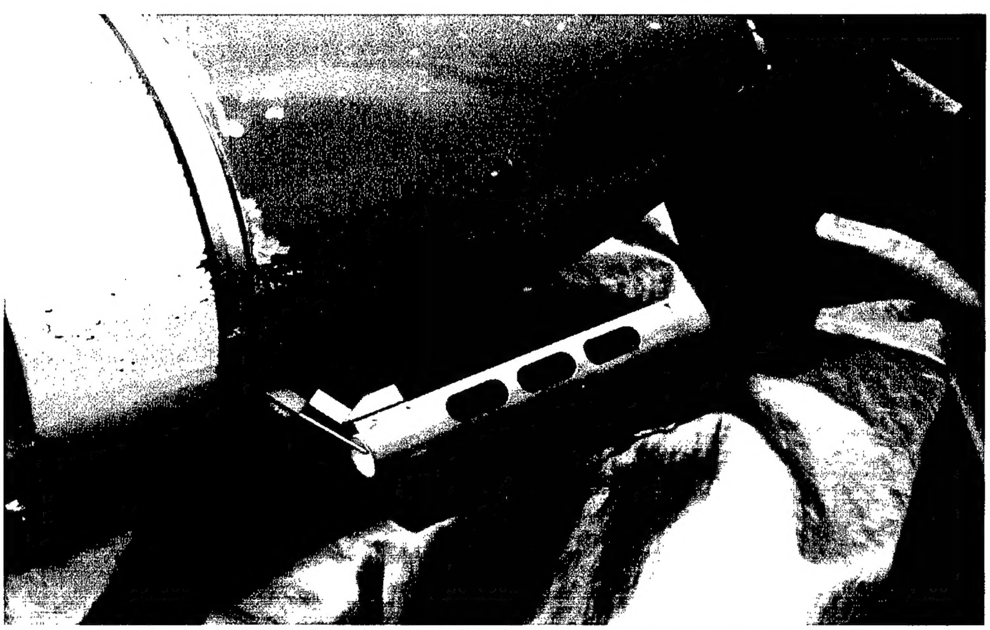

Figure 9 Ducted WRC-Seabird CTD sensor (not pumped)

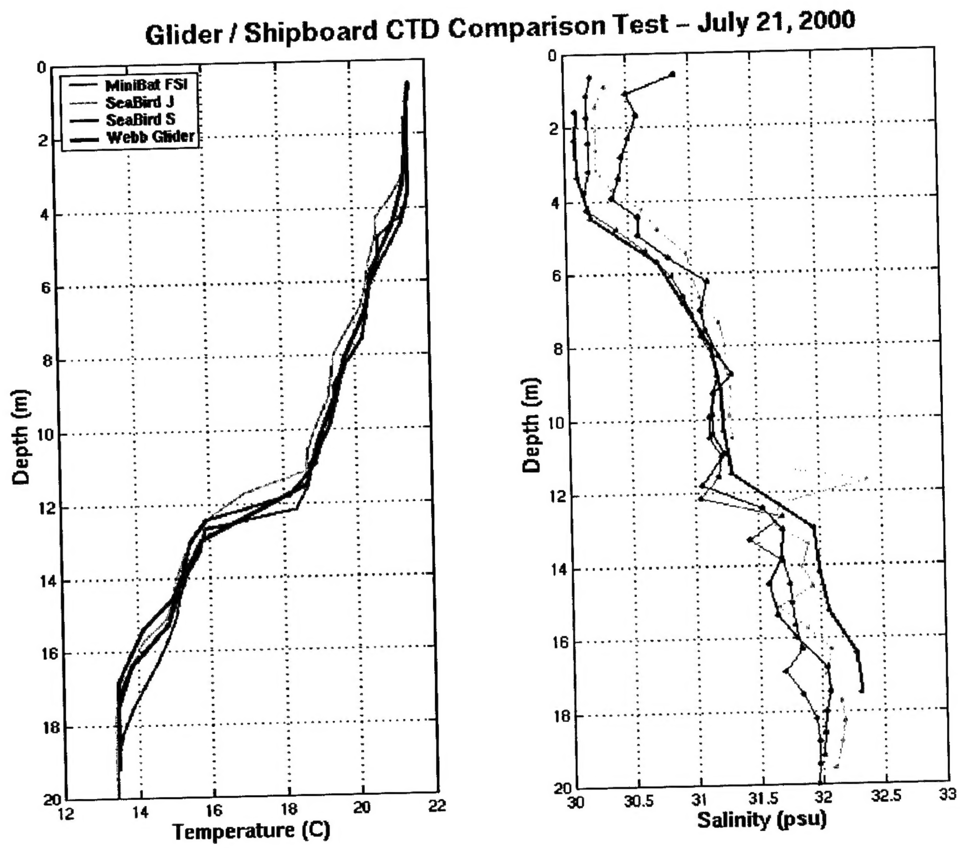

Figure 10 CTD comparison

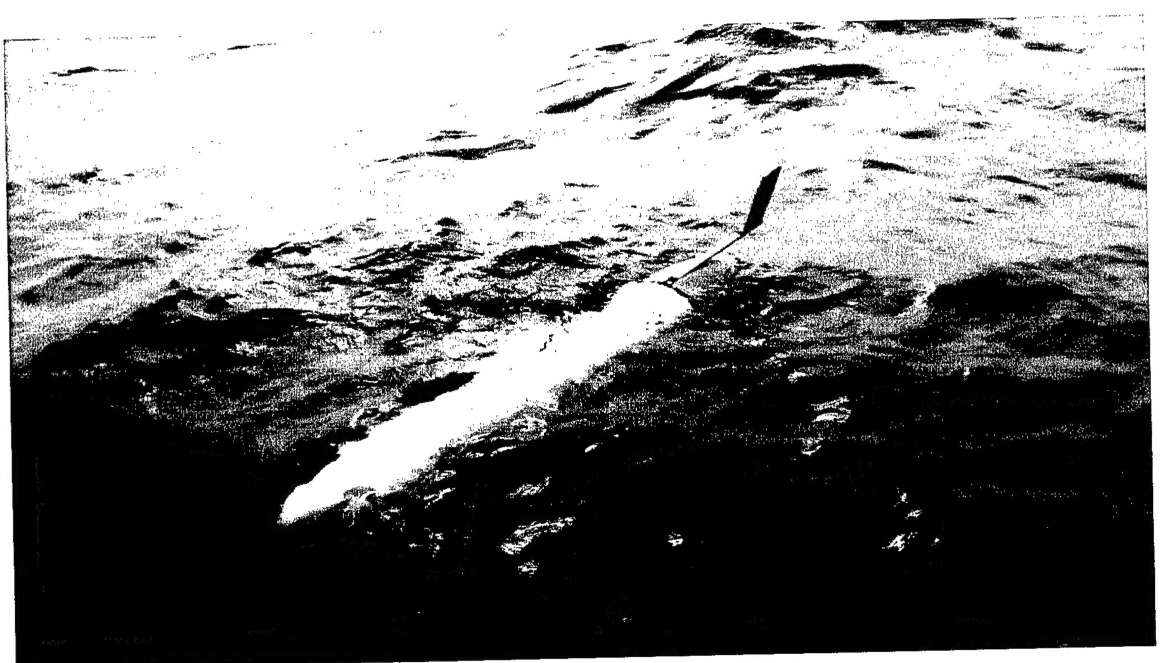

Figure 11 Tail (Antenna) Fin